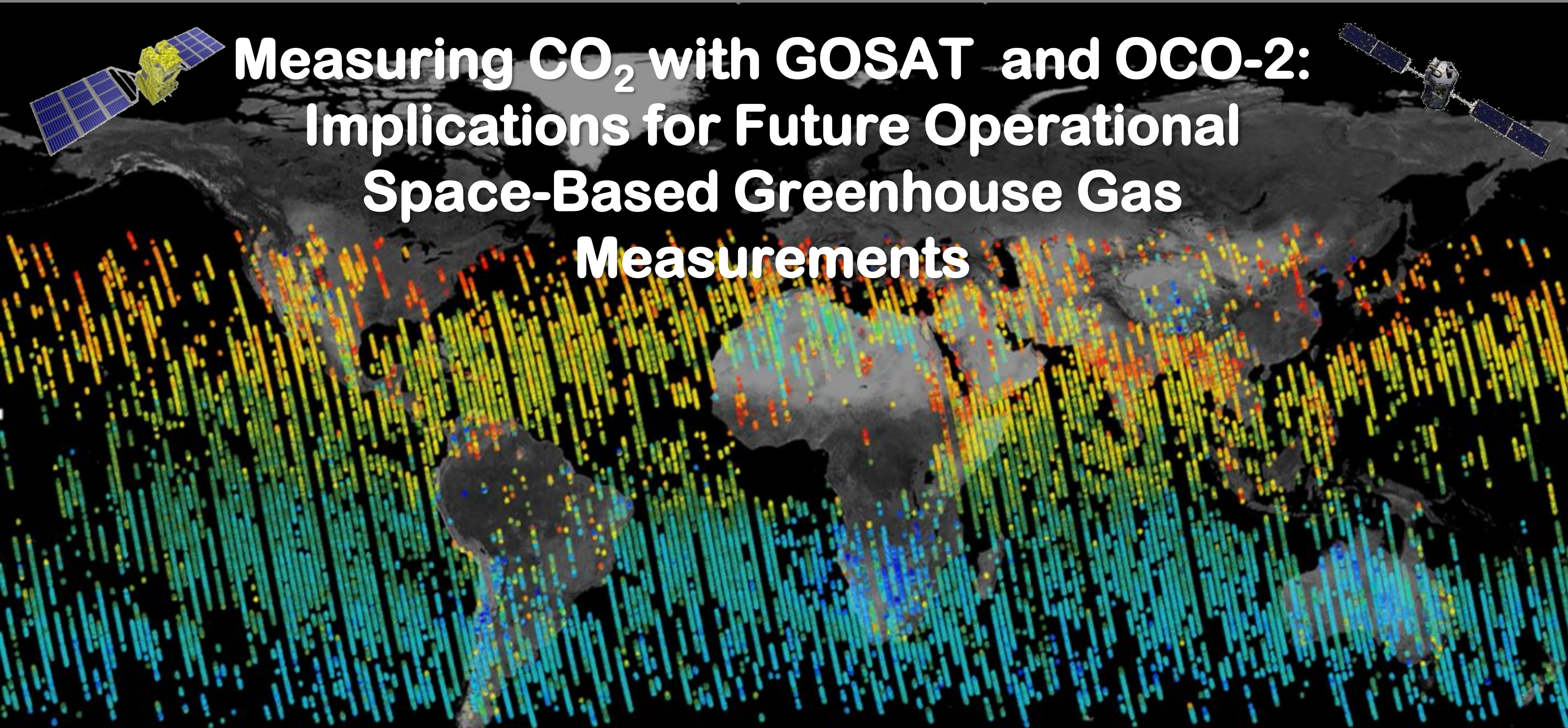
Measuring CO_2 with GOSAT and OCO-2: Implications for Future Operational Space-Based Greenhouse Gas Measurements



David Crisp, Jet Propulsion Laboratory, California Institute of Technology

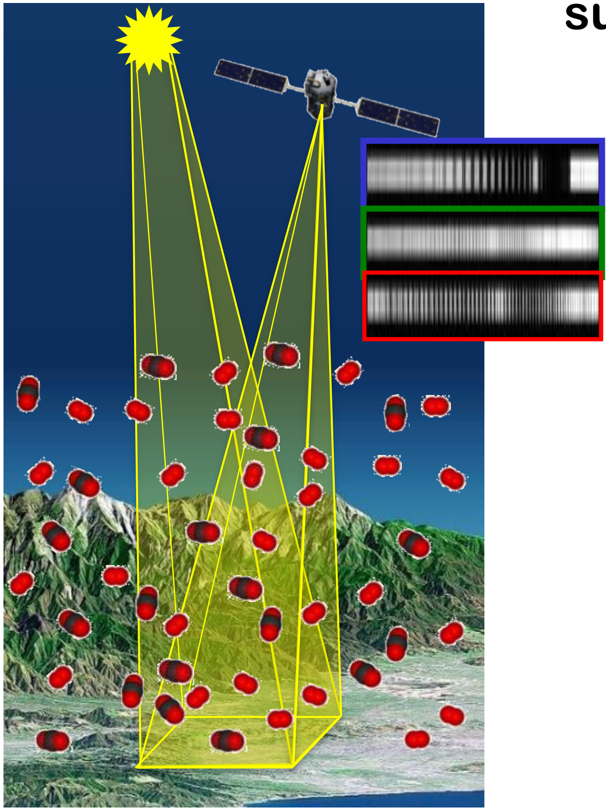
2 October 2017

Need for space-based measurements of CO_2 and CH_4

- Reduce uncertainty in fossil fuel emission inventories and their time evolution
  - Discriminate and quantify anthropogenic emissions in context of natural carbon cycle
  - Provide a consistent global method for validating GHG inventories
  - Address new requirements from UNFCCC Paris agreement (e.g. “global stocktaking”)
- Monitor and predict changes in the natural carbon cycle associated with climate change and human activities
  - Deforestation, degradation, fire
  - Changes in CO_2 and CH_4 associated with drought, temperature stress, melting permafrost
  - Changes in ocean thermal structure and dynamics

Measuring CO_2 from Space

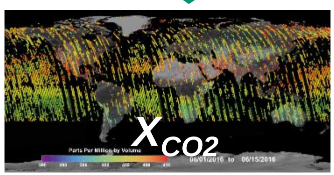
- **Record** spectra of CO_2 and O_2 absorption in reflected sunlight



Retrieve variations in the column averaged CO_2 dry air mole fraction, X_{CO2} over the sunlit hemisphere

Initial Surf/Atm State → **Radiative Transfer Model** → **Instrument Performance Model** → **Inverse Model** → Revised Surf/Atm State → **Radiative Transfer Model**

Inverse Model →



Validate measurements to ensure X_{CO2} accuracy of 1 ppm (0.25%)

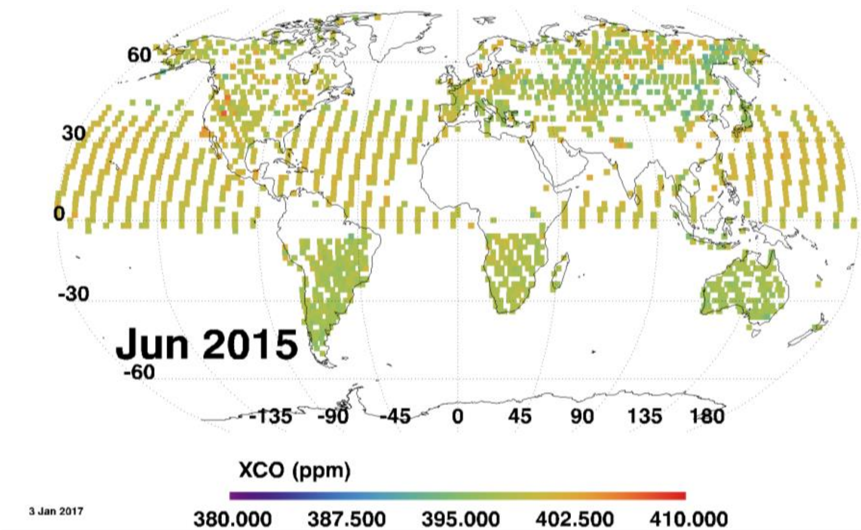
Estimating Fluxes from Space-based CO_2 Measurements

Estimating surface fluxes of CO_2 or CH_4 from space-based observations of reflected sunlight is a 6-step process:

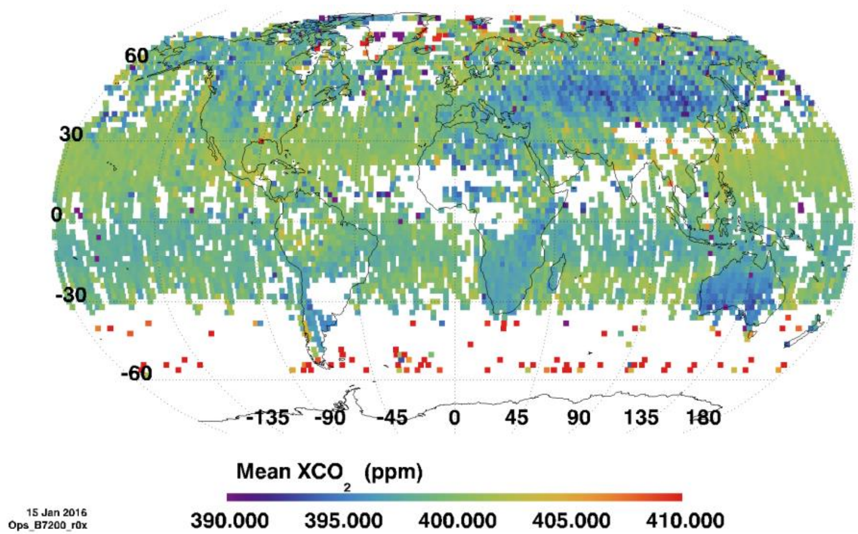
1. Acquire high spectral resolution, co-bore-sighted observations within near infrared CO_2 and O_2 bands at high spatial resolution over the sunlit hemisphere
2. Calibrate these measurements to yield spectral radiances
3. Use remote sensing retrieval algorithms to estimate the column-averaged CO_2 and CH_4 dry air mole fractions, X_{GHG}, and other state properties from each sounding
4. Validate the X_{GHG} estimates against available standards
5. Perform a flux inversion to estimate the surface GHG fluxes needed to maintain the observed X_{GHG} distribution in the presences of the prevailing winds
6. Validate retrieved fluxes against available standards

Retrieving X_{CO2} from GOSAT and OCO-2 Data

GOSAT



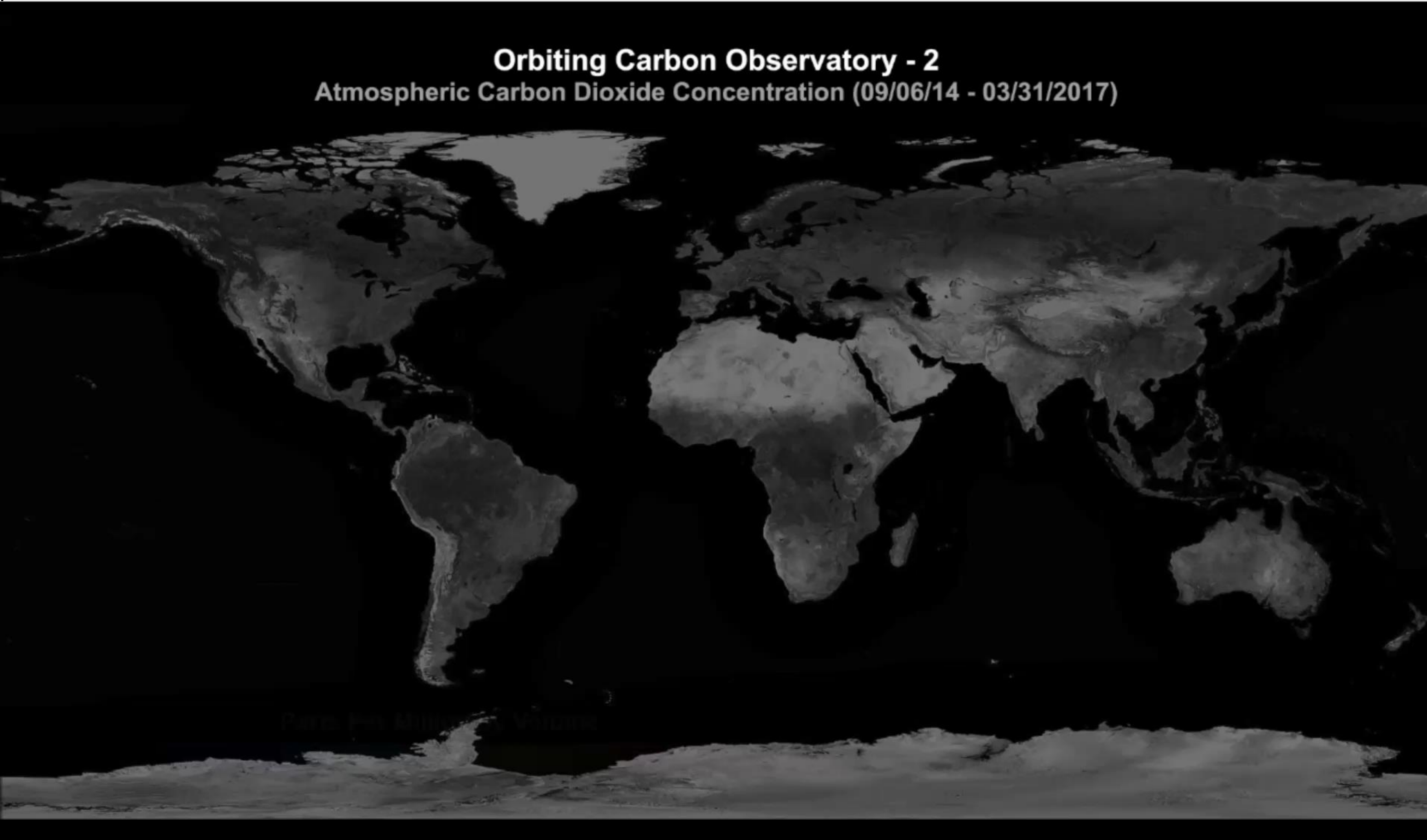
OCO-2



GOSAT TANSO-FTS has been returning 300-100 cloud free soundings/day since Apr 2009. The ACOS/GOSAT team has been using these data to retrieve X_{CO2}.

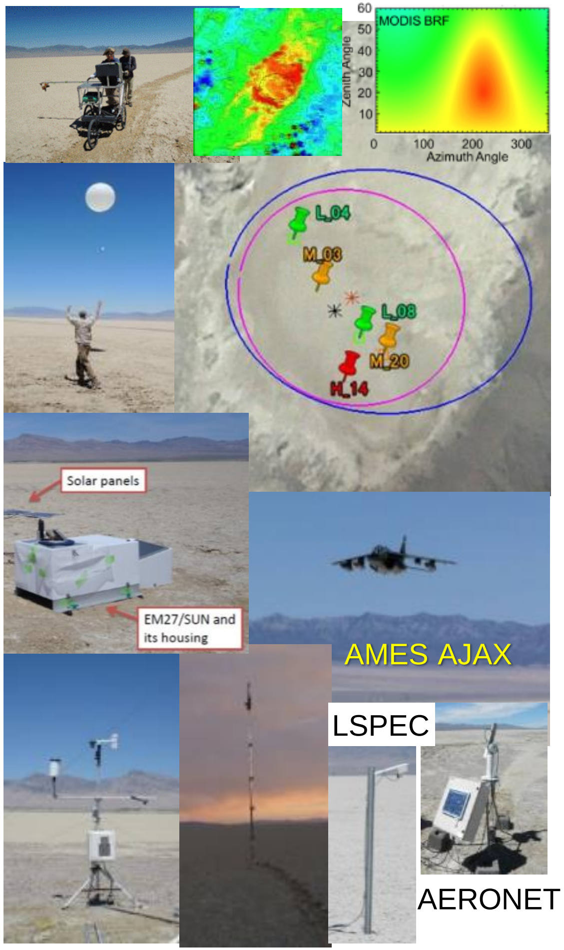
OCO-2 has been returning 25000 to 70000 soundings/day since Sept 2014. The ACOS/GOSAT algorithm was modified to retrieve X_{CO2} from these data.

A Quick Look at the OCO-2 Prime Mission



Creating a Combined Data Product: the OCO-2/GOSAT Collaboration

Vicarious Calibration



Retrieval Algorithm

Forward Radiative Transfer Model
Spectra + Jacobians

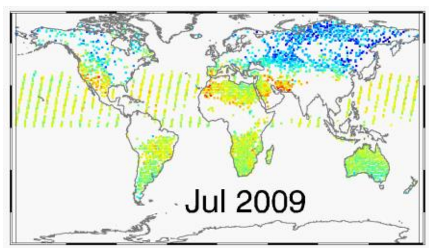
Instrument Model
Spectral+Polarization

Inverse Model
- Compare obs. & simulated spectra
- Update State Vector

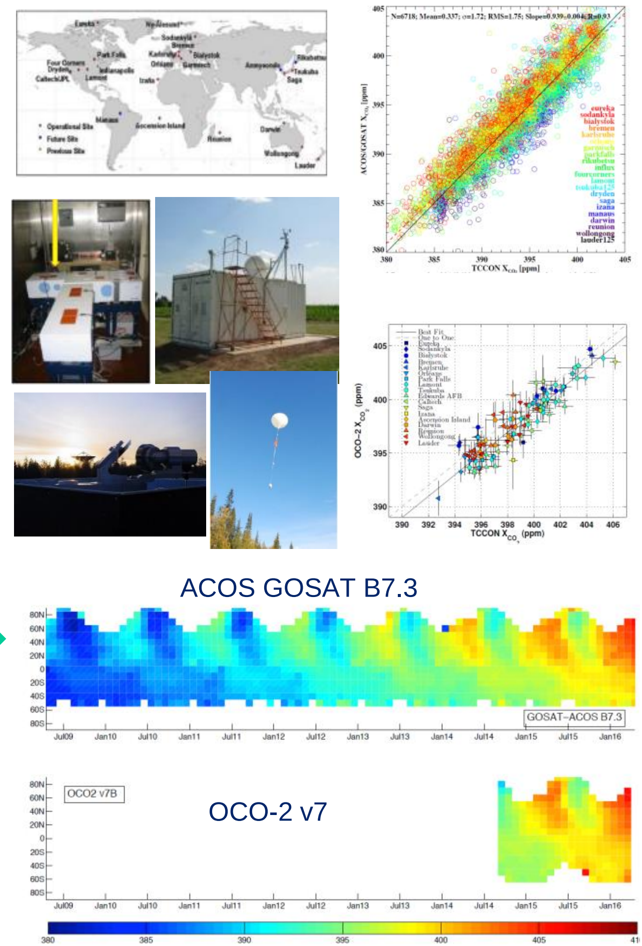
?

not converged

converged

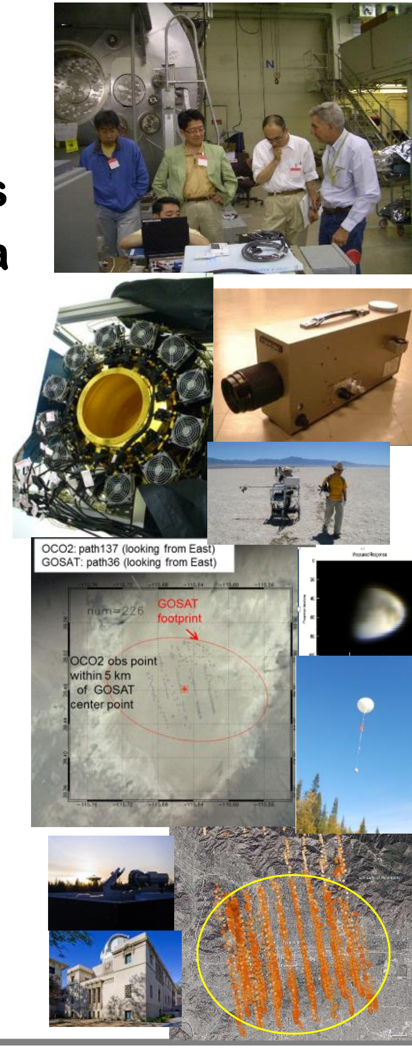


Cross Validation

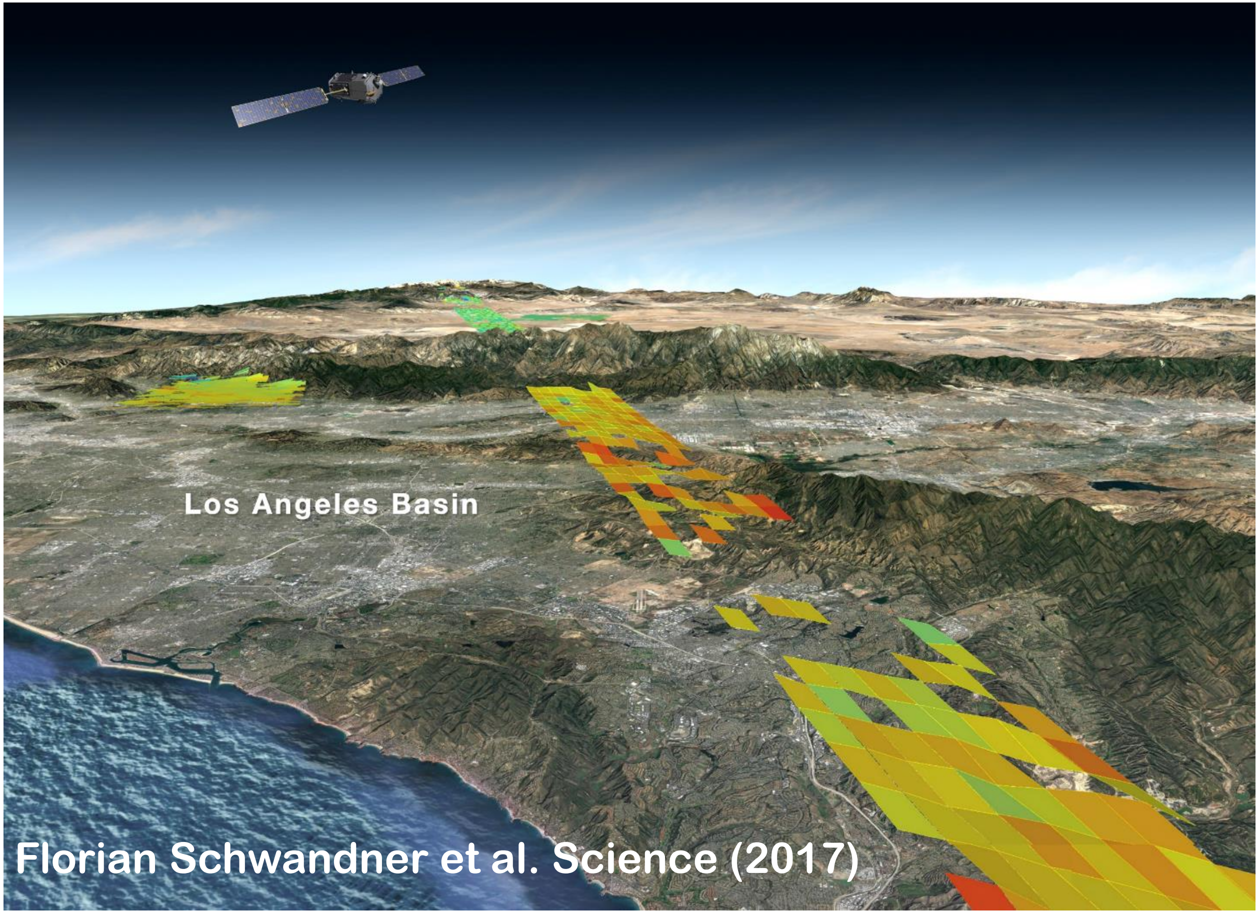


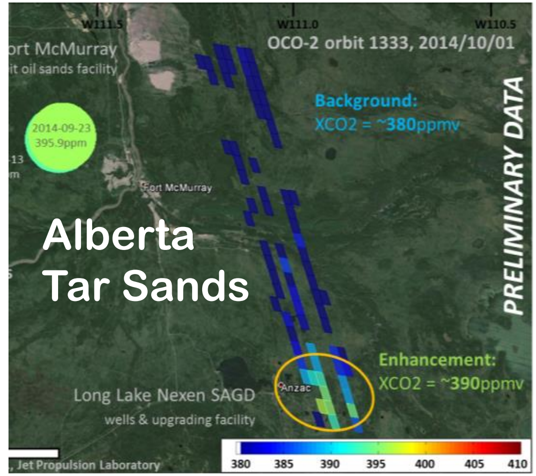
Lessons Learned from GOSAT and OCO-2: Cross-Calibration and Cross Validation

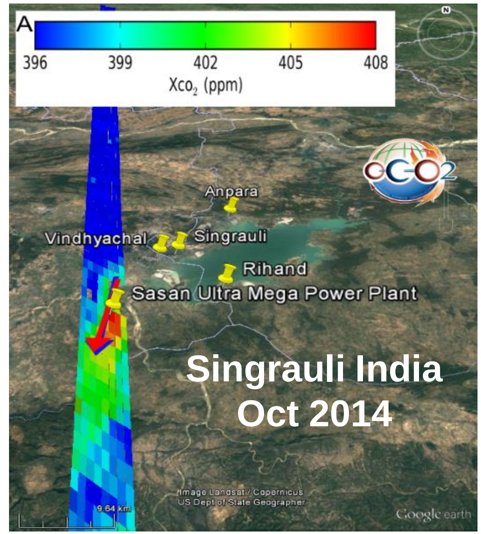
- Pre Launch:
  - Exchange information on best practice for pre-launch instrument characterization
  - Cross calibration of pre-launch radiometric standards
  - Exchange of gas absorption coefficient and solar data
  - Retrieval algorithm development/intercomparison
  - Validation system development (TCCON, aircraft)
  - Multi-Satellite OSSE's – what do you gain with truly coordinated observations
- Post Launch:
  - Cross calibration of solar/lunar/Earth(vicarious: RRV+?) observations
  - Including exchange of solar and lunar standards
  - Cross validation: TCCON, EM27/Sun, and aircraft validation campaigns
  - Continued retrieval algorithm development/intercomparisons



Quantifying Localized Sources



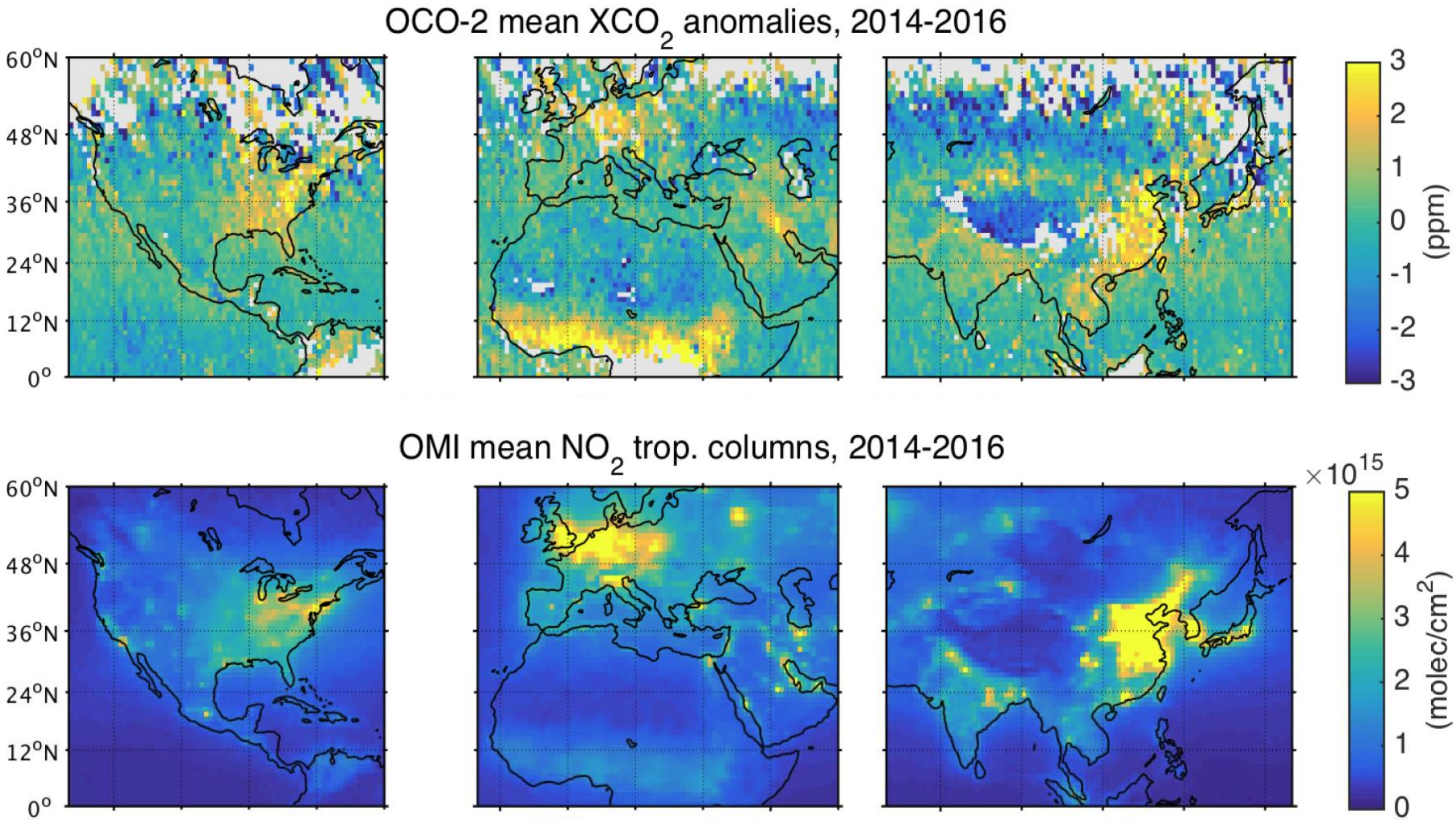




Nassar et al. (GRL 2017)

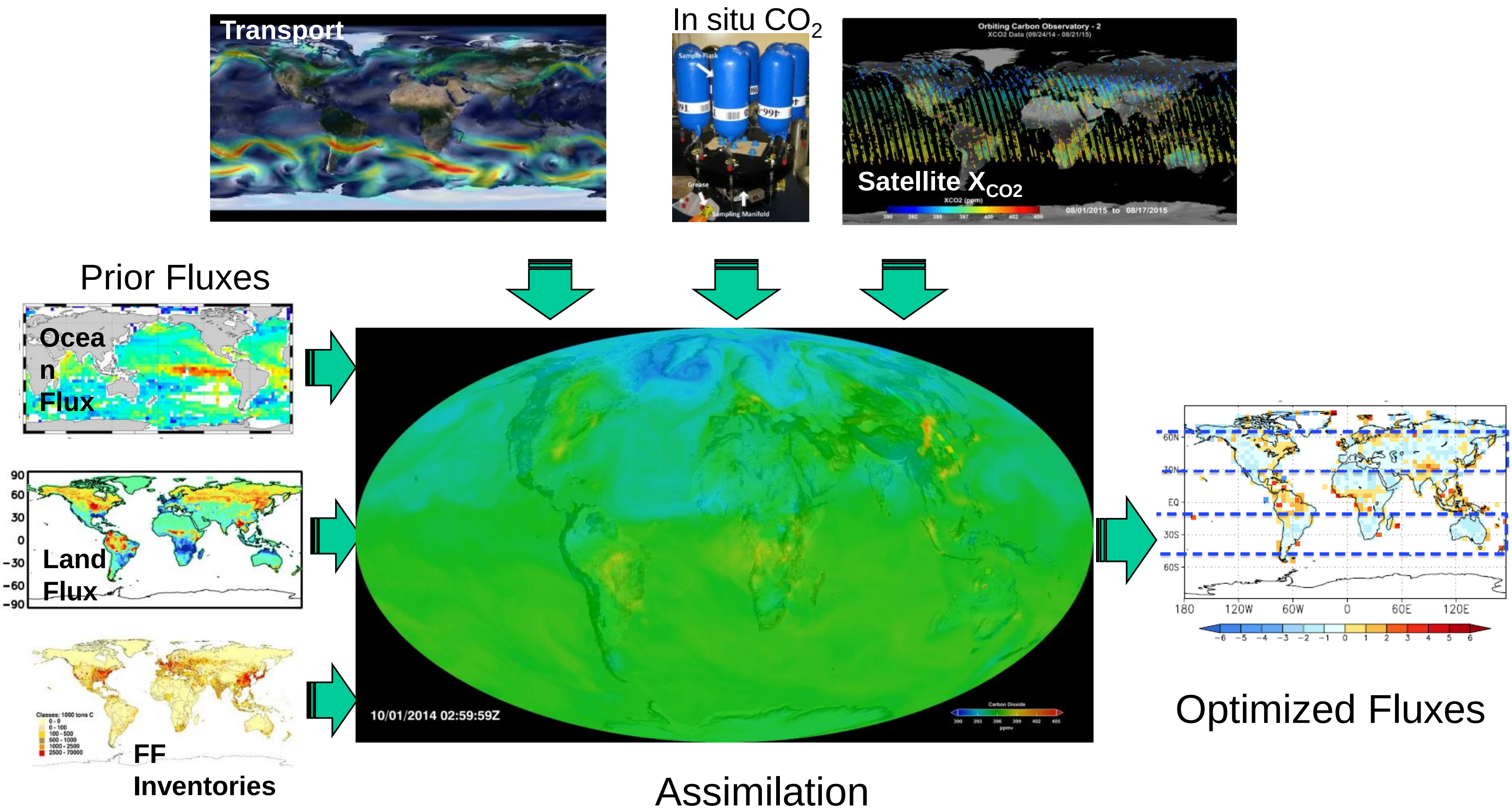
High spatial resolution and full coverage are critical for quantifying localized sources

Anthropogenic Emissions

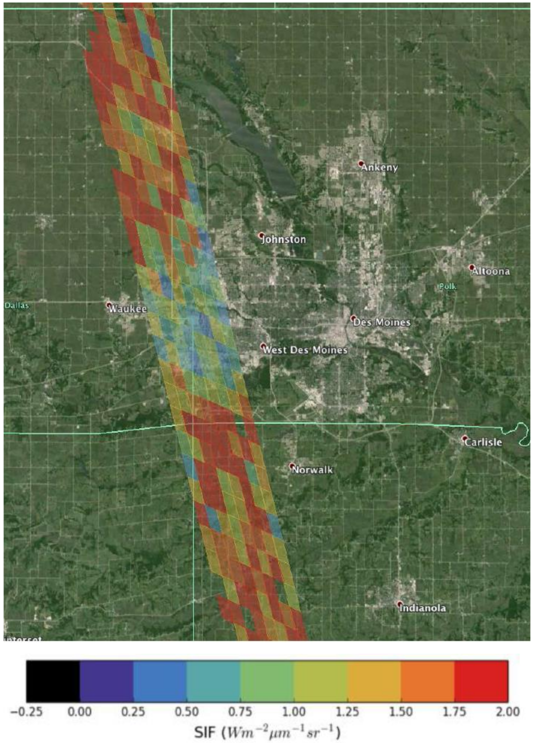


Janne Hakkarainen et al. GRL (2016)

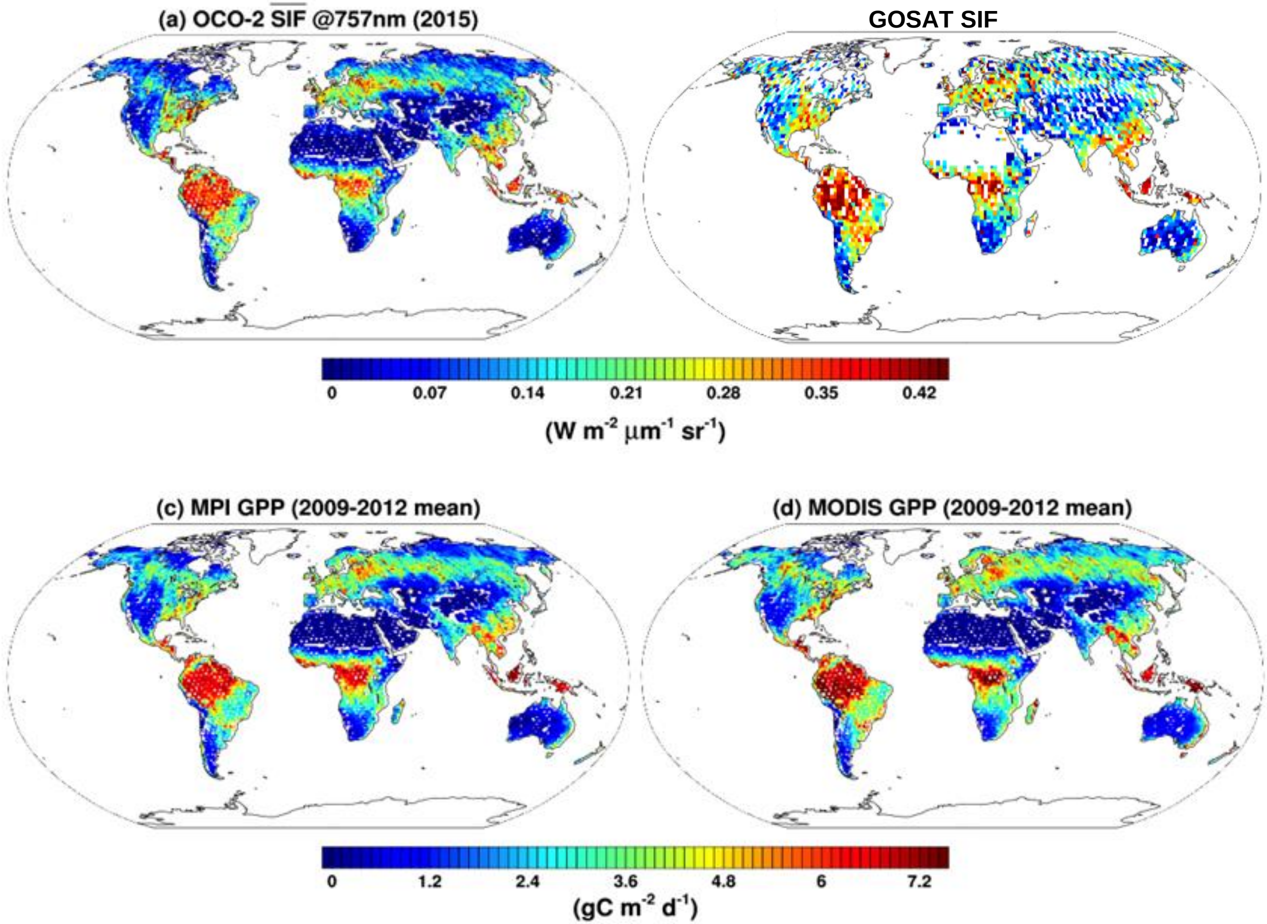
“Top-Down” Flux Inversion Estimates



Solar Induced Chlorophyll Fluorescence (SIF)



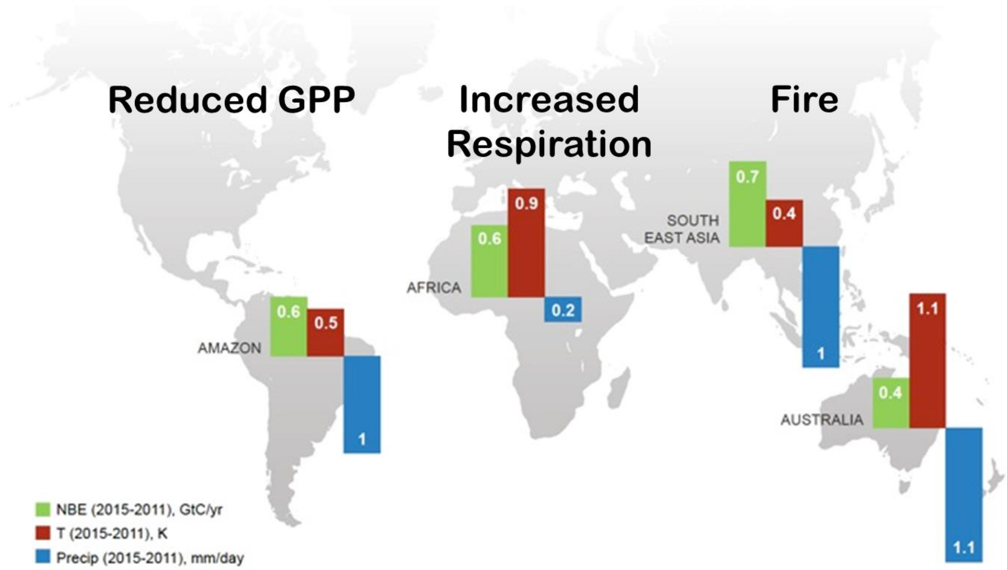
OCO-2 SIF over Des Moines, Idaho



Sun et al. (Science 2017)

Biospheric Fluxes: Relative Roles of heat, drought and fires in 2015 El Niño

- **Question**: Are fires, high temperatures or drought responsible for increases in carbon release during El Niños?
- **Approach:** X_{CO2} and SIF estimates from OCO-2 and GOSAT were combined with satellite MOPITT CO measurements and other data
- **Results**: In South America, plants went dormant due to heat and drought; in Africa, high temperatures enhanced plant respiration; in Asia, drought and heat increased the intensity of fires



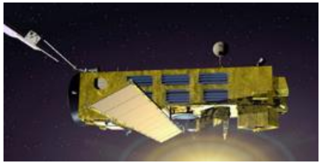
Significance: OCO-2 and GOSAT provide the first direct constraints of the relative roles of heat, drought, and fires on the regional CO_2 exchange during El Niño years.

Liu et al. (Science 2017)

Lessons Learned from GOSAT & OCO-2

- High accuracy and low bias are both essential
- High spatial resolution (footprint area < 4 km^2)
  - Critical for quantifying emissions from compact sources
    - X_{CO2} anomaly associated with a given CO_2 injection is inversely proportional to the area of the footprint
  - Critical for gathering data in presence of patchy clouds
- Imaging rather than sampling the CO_2 and CH_4 field
  - Critical for tracking emission plumes and resolving anthropogenic emission sources from the natural background
- High resolution transport models for flux inversion
  - Critical for quantifying at the scale of cities and resolving anomalies associated with CO_2/CH_4 “weather”
- Proxies (SIF, CO, and NO_2) may be needed for attribution

Remote Sensing of CO_2 and CH_4 using Reflected Sunlight: The Pioneers



- **SCIAMACHY (2002-2012)** – First sensor to measure O_2, CO_2, and CH_4 using reflected NIR/SWIR sunlight
  - Regional-scale maps of X_{CO2} and X_{CH4} over continents

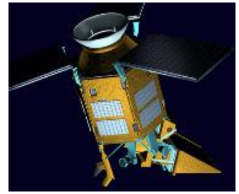
- **GOSAT (2009 …)** – First Japanese GHG satellite
  - FTS optimized for hgh spectral resolution over broad spectral range, yielding CO_2, CH_4, and chlorophyll fluorescence (SIF)

- **OCO-2 (2014 …)** – First NASA satellite to measure O_2 and CO_2 with high sensitivity, resolution, and coverage
  - High resolution imaging grating spectrometer small (< 3 km^2) footprint and rapid sampling (10^6 samples/day)

- **TanSat (2016 …)** - First Chinese GHG satellite
  - Imaging grating spectrometer for O_2 and CO_2 bands and cloud & aerosol Imager
  - In-orbit checkout formally complete in August 2017

Remote Sensing of CO_2 and CH_4: The Next Generation

- **Feng Yun 3D (2017)** – Chinese GHG satellite on an operational meteorological bus
  - GAS FTS for O_2, CO_2, CH_4, CO, N_2O, H_2O



- **Sentinel 5p (2017)** - Copernicus pre-operational Satellite
  - TROPOMI measures O_2, CH_4 (1%), CO (10%), NO_2, SIF
  - Imaging at 7 km x 7 km resolution, daily global coverage

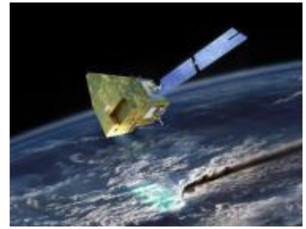
- **Gaofen 5 (2018)** - 2nd Chinese GHG Satellite
  - Spatial heterodyne spectrometer for O_2, CO_2, and CH_4

- **OCO-3 (2018*)** – NASA OCO-2 spare instrument, on ISS
  - First solar CO_2 sensor to fly in a low inclination, precessing orbit

- **GOSAT-2 (2018)** – Japanese 2nd generation satellite
  - CO as well as CO_2, CH_4, with improved precision (0.125%), and active pointing to increase number of cloud free observation

Future GHG Satellites

- **CNES/UK MicroCarb (2020)** – compact, high sensitivity
  - Imaging grating spectrometer for O_2 A, O_2 $^1\Delta_g$, and CO_2
  - ~1/2 of the size, mass of OCO-2, with 4.5 km x 9 km footprints



- **CNES/DLR MERLIN (2021)** - First CH_4 LIDAR (IPDA)
  - Precise (1-2%) X_{CH4} retrievals for studies of wetland emissions, inter-hemispheric gradients and continental scale annual CH_4 budgets

- **NASA GeoCarb (2022*)** – First GEO GHG satellite
  - Imaging spectrometer for XC_{O2}, X_{CH4}, X_{CO} and SIF
  - Stationed above 85° E for North/South America

- **Sentinel 5A,5B,5C (2022)** - Copernicus operational services for air quality and CH_4
  - Daily global maps of X_{CO} and X_{CH4} at < 8 km x 8 km
- Sentinel 7 (2025+) – Copernicus Operational CO2 Satellite

Advantages of Integrating Near-term Missions into a Virtual Constellation

A multi-satellite GHG constellation could

- Exploit the benefits of observations from low Earth orbit (LEO), geostationary orbits (GEO), and Highly Elliptical Orbits (HEO)
- Reduce revisit times in the presence of optically-thick clouds
- Improve spatial coverage without requiring very broad swaths that
  - Are technically difficult and expensive to implement
  - Large atmospheric path lengths at the swath edges are more likely to be contaminated by clouds
- Collect coincident observations of proxies (CO, NO_2, SIF) to facilitate the interpretation of the measurements
- Provide resiliency to the loss/degradation of individual satellites
- Facilitate data quality improvements through cross calibration and cross validation

Partnerships will help realize these objectives

Candidate Architectures for Purpose-Built GHG Constellations

The coverage, resolution, and precision requirements could be achieved with a constellation that incorporates

- A constellation of (3 or more) satellites in LEO with
  - Broad (~200) km swath with mean footprint sizes < 4 km^2
  - Single sounding random error near 0.5 ppm and small regional scale biases (< 0.1 ppm) over > 80% of the sunlit hemisphere
  - One (or more) satellites carrying ancillary sensors (CO, NO_2, SIF and/or a CO_2 or CH_4 Lidar)
- A constellation with 3 (or more) GEO satellites
  - Monitor diurnally varying processes (e.g. rush hours, diurnal variations in the biosphere)
  - Stationed over Europe/Africa, North/South America, and East Asia
- One or more and one or more HEO satellites to monitor carbon cycle changes in the high arctic

Moving Forward from “Science” to “Operational” GHG Missions

- With the exception of the Sentinels, all of the existing and planned GHG missions are “science” missions, designed to identify optimal methods for measuring CO_2 and CH_4, not “operational” missions designed to deliver policy relevant GHG products focused on anthropogenic emissions
- Following the model developed by the operational meteorological satellite constellation, future GHG constellations will also need to focus on
  - Orbit and mission coordination
  - Data distribution, exchange, and format requirements
  - Focused efforts to improve and validate flux inversion models
- To fully exploit the information collected by future GHG constellations, the missions would also have to invest in training and capacity building and public outreach

Summary

- Space-based remote sensing observations hold substantial promise for future long-term monitoring of greenhouse gases
  - These data complement existing ground-based and aircraft based in situ data with increased coverage and sampling density
- The GOSAT and OCO-2 missions are beginning to demonstrate these capabilities
  - GOSAT and OCO-2 teams have pioneered methods for cross-calibrating measurements and cross-validating products
  - Their products have been combined to produce an 8-year record that is now being used in studies of the global carbon cycle
- Over the next decade, a succession of missions with a range of CO_2 and CH_4 measurement capabilities will be deployed
  - Much greater benefits could be achieved if these sensors can be cross-calibrated and their products can be cross-validated so that they can be combined into a long, continuous GHG data record